

The Use of Aerodynamic and Wind Climatological Databases for High-Rise Reinforced Concrete Structure Design

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ABSTRACT

Structural response due to directional wind must be taken into account rigorously and transparently in wind resistant design, particularly for tall buildings. A database-assisted design (DAD) technique makes it possible to account for directional effects on the structural design of tall buildings. To this end, DAD employs a climatological database consisting of the directional wind speeds at a meteorological station relevant to the building site, an aerodynamic database of the pressure coefficient time histories at large numbers of taps on the exterior building surface, and a micrometeorological data set consisting of the ratio of wind speeds at the standard elevation at that site to the mean hourly wind speeds at the top of the building. This study describes the application of the DAD methodology to the design of a 60-story reinforced concrete structure using the aerodynamic and wind climatological databases. The DAD procedure provides wind-induced responses with any mean recurrence interval, including demand-to-capacity indexes, inter-story drifts, and top-floor accelerations, and compares their compliance with design criteria.

Keywords: Database-Assisted Design (DAD); climatological database; mean recurrence interval; reinforced concrete; wind effects.

INTRODUCTION

Extreme wind speeds, aerodynamic pressures, and the dynamic response of tall buildings are functions of wind direction. The directional dependence must be taken into account clearly and rigorously in the wind resistant design of tall buildings. The database-assisted design (DAD) technique makes it possible to account for the directional effects on the structural design of tall buildings by employing (1) a directional database of the wind speeds at a meteorological station relevant to the building site (i.e., a wind climatological data set, containing, for a large number of storm events, the respective directional wind speeds; the dataset can be developed by Monte Carlo simulation, from smaller datasets of measured wind speeds), (2) a directional database of the pressure coefficient time histories at a sufficiently large number of ports on the exterior building surface, and (3) a micrometeorological data set obtained in the wind tunnel and consisting of the ratio between the directional mean hourly wind speeds at the top of the building and the corresponding directional 3-s or 10-min wind speeds at the standard elevation (typically 10 m) of the meteorological site.

Once the databases (1) and (2) and the data set (3) are made available by the wind engineering consultant, the structural engineer can independently perform the requisite structural calculations and design. The clear division of tasks between the wind engineer and the structural engineer has the advantage of transparency and accountability, in the sense that the wind loading information inherent in the data of (1), (2), and (3) is clearly defined and recorded. If the quality of the wind speed record at the location of concern is relatively unsatisfactory, as can be the case in areas where wind speed data have not been collected over sufficiently long time periods, the assumptions used to develop the requisite wind climatological database (1) must be clearly stated. This provides a basis for developing, via accepted structural reliability techniques, more realistic uncertainty estimates for the response calculations than would be the case if standard safety margins (load factors) or mean recurrence intervals of the wind effects were simply taken from standard provisions developed for ordinary structures under reasonably well known wind climatological conditions. The DAD procedure is illustrated in the paper with reference to a building with reinforced concrete frames.

OVERVIEW OF DAD PROCEDURE

The DAD approach to high-rise buildings is represented in Figure 1. The processes within the box constitute the main algorithm of the High-Rise Database-Assisted Design for Reinforced Concrete structures (HR_DAD_RC) software (Yeo 2010). The DAD procedure is described as follows.

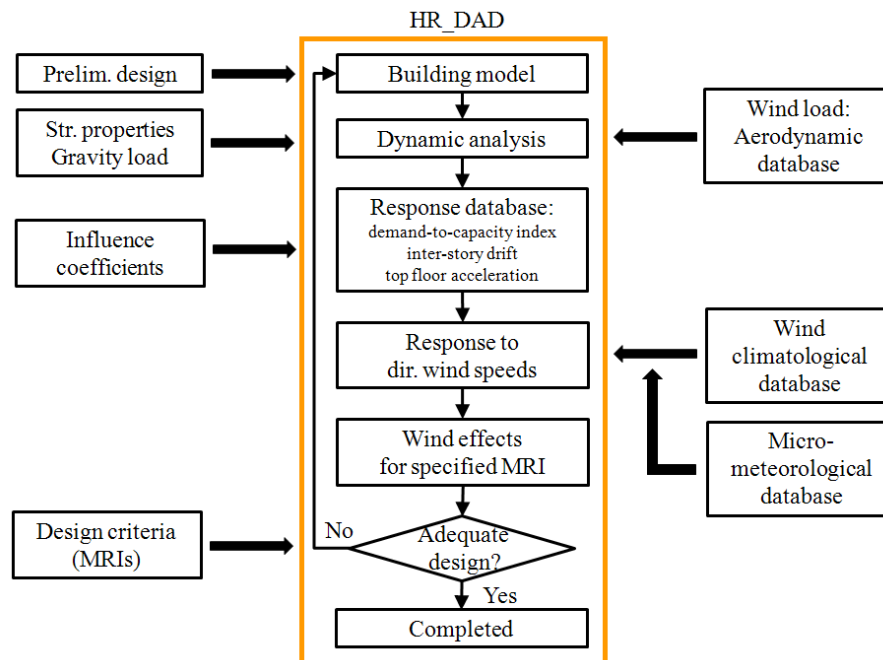


Figure 1. Basic algorithm for HR_DAD

Preliminary design

A preliminary design, performed by the structural engineer, provides *an initial set of structural properties* including building member dimensions. The fundamental natural frequencies of vibration for the preliminary design can be obtained by modal analysis using a finite elements analysis program. The damping ratios are specified by the structural engineer.

Dynamic analysis

Dynamic analyses of the building with the member dimensions determined in the preliminary design employ combinations of wind and gravity loads specified in the ASCE 7-10 Standard (hereinafter ASCE 7-10), Section 2.3 (ASCE 2010). The wind loads in DAD are calculated from the aerodynamic database for each given wind direction. The pressure time histories can be obtained from wind tunnel tests or, in principle, from CFD simulations.

The dynamic analyses are performed by considering the resultant of the wind forces at each floor's mass center, for each wind direction and for reference mean hourly wind speeds at the top of the building of, for example, 20 m/s, 30 m/s, ..., 80 m/s, depending upon the wind speed range of interest at the building location. The directional wind forces acting on each floor are calculated from directional aerodynamic pressures database provided by the wind engineering consultant. The outputs of this phase are the *floor displacements, floor accelerations, and effective (aerodynamic plus inertial) lateral forces at each floor corresponding to the specified set of directional reference wind speeds*.

Influence coefficients for determining internal forces

For each direction and specified wind speed, a time series of internal forces in members were calculated using the effective lateral forces at floor mass centers multiplied by the *influence coefficients* that yield the internal forces due to a unit load with specified direction acting at the mass center of any floor.

Response database

Peak wind effects of demand-to-capacity indexes, inter-story drifts, and top-floor accelerations can be obtained from: time series of internal forces due to wind and gravity loads; floor displacements; and floor accelerations. Using interpolation techniques the structural response can be obtained for any specific wind direction and speed within the specified ranges. The response database is a property of the structure that incorporates its aerodynamic and mechanical characteristics and is independent of the wind climate.

Wind climatological database

A *wind climatological database*, developed by wind engineers, is a matrix of directional wind speeds at 10 m above ground in open exposure, and is developed for a location close to the building of interest. Each row of the matrix corresponds to one storm event (if a peaks-over-threshold estimation procedure is used) or to the largest yearly speed (if an epochal estimation procedure is used). The columns of the matrix correspond to the specified wind directions. For hurricane winds, a similar matrix of wind speeds is used. Using micro-meteorological relations,

reference wind speeds in the wind climatological database are converted to mean hourly wind speeds at the elevation of the top of the building.

Peak directional response

For each direction of each storm event (or year), the peak response of interest is calculated by interpolation from the response database. From a design viewpoint, however, only the largest peak response is retained for each storm event (or year). A vector of the maximum response induced by each storm event is thus created, and its dimension is equal to the number of storm events in the wind climatological database.

Peak wind effects with specified MRIs

The time series of peak wind effects induced by each storm event in the wind climatological database is used to obtain the requisite peak wind effect with the specified MRI. The time series is rank-ordered, the largest wind effect having rank one, and the non-parametric estimation method described in Sect. 2.4.3.2.2 of Simiu and Miyata (2006) can be employed. Note that the estimated peak responses with specified mean recurrence intervals are obtained for wind load effects, not for wind loads.

Based on the assumption that the occurrence of storm events is a Poisson process with constant occurrence rate, the estimated MRI \overline{N}_k associated with k^{th} ranked peak wind effects is

$$\overline{N}_k = \frac{n+1}{vk} \quad (1)$$

where n is total number of storm events in the database. Interpolation is used where necessary.

Adjustment of demand-to-capacity indexes

According to ASCE 7-10, Section 31.4.3, it is prudent for estimates based on the wind tunnel method to be not less than 80 % of the corresponding estimates based on the ASCE 7 analytical method using directional or envelope procedure. For practical reasons this requirement applies to estimates of peak overturning moments in the principal axes with MRIs specified in the Standard. If DAD-based overturning moments do not satisfy this requirement the demand-to-capacity index is adjusted as:

$$B_{ij}^* = \gamma B_{ij} \quad (2)$$

$$\gamma = \frac{0.8}{M_o^{DAD} / M_o^{ASCE7}}$$

where M_o^{DAD} and M_o^{ASCE7} are the overturning moments at base obtained from DAD and ASCE 7-10, respectively, and γ is the index adjustment factor.

Compliance with design criteria

Once peak responses (i.e., demand-to-capacity index, inter-story drift, and acceleration) for specified MRIs are obtained, DAD verifies if the peak responses satisfy design criteria for safety and serviceability. The procedure outlined in Figure 1 is repeated as needed with a modified structural design (e.g., by re-sizing members or by installing dampers) until the results satisfy the design criteria.

Structural responses considered in design

The DAD methodology for safety and serviceability of a RC structure satisfies design specifications in the Building Code Requirements for Structural Concrete and Commentary 318-08 (hereinafter ACI 318-08) and ASCE 7-10 Standards. The responses considered are the demand-to-capacity index, the inter-story drift, and accelerations at the top floor.

Demand-to-capacity indexes

A demand-to-capacity index (DCI) is a quantity used to measure the adequacy of a structural member's strength. In general, this index is defined as a ratio or sum of ratios of the internal force induced by design loads to associated strength provided by the section. An index higher than unity indicates inadequate design of a structural member. For reinforced concrete two demand-to-capacity indexes are of interest: B_{ij}^{PM} for axial and/or flexural loads, and B_{ij}^{VT} for shear and torsion. The index " B_{ij}^{PM} " pertains to the interaction of axial and/or flexural loads for columns and beams:

$$\begin{aligned} B_{ij}^{PM} &= \frac{M_u}{\phi_m M_n} && \text{(for a tension-controlled section)} \\ &= \frac{P_u}{\phi_p P_n} && \text{(for a compression-controlled section)} \end{aligned} \quad (3)$$

where M_u and P_u are the factored bending moment and axial force at the section, M_n and P_n are the nominal moment and axial strengths at the section, and ϕ_m and ϕ_p are the reduction factors for flexural and axial strengths, respectively. In particular, for columns subject to bi-axial flexure loads, the Bresler reciprocal load method of R10.3.6 in ACI 318-08 (2008) is used for compression-controlled sections, and the PCA (Portland Cement Association) load contour method (PCA 2008) is used for tension-controlled sections.

The index " B_{ij}^{VT} " is associated with interaction equations for shear forces and torsional moment for columns and beams:

$$B_{ij}^{VT} = \frac{\sqrt{V_{ux}^2 + V_{uy}^2 + \left(\frac{T_u p_h b_w d}{1.7 A_{oh}^2} \right)^2}}{\phi_v (V_c + V_s)} \quad (4)$$

where V_c and V_s are the nominal shear strengths provided by concrete and by reinforcement, respectively. V_{ux} and V_{uy} are the shear forces in the x and y axes, respectively. T_u is the torsional moment, ϕ_v is the reduction factors for shear strengths, p_h is the perimeter enclosed by the centerline of the outermost closed stirrups, A_{oh} is the area enclosed by the centerline of the outermost closed stirrups, b_w is the width of the member, and d is the distance from extreme compression fiber to the centroid of longitudinal tension reinforcement.

Inter-story drift

A time series of the x -axis inter-story drift ratios at the i^{th} story, $d_{i,x}$ is

$$d_{i,x}(t) = \frac{[x_i(t) - D_{i,y}\theta_i(t)] - [x_{i-1}(t) - D_{i-1,y}\theta_{i-1}(t)]}{h_i} \quad (5)$$

where $x_i(t)$ and $\theta_i(t)$ are the displacement and rotation at the mass center at the i^{th} floor, respectively, $D_{i,x}$ is the distance along the x axis from the mass center on the i^{th} floor to the point of interest on that floor, and h_i is the i^{th} story height between mass centers of the i^{th} and the $i-1^{\text{th}}$ floor. A similar expression holds for the y -direction.

The ASCE 7-10 Commentary suggests limits on the order of 1/600 to 1/400 (see Appendix CC.1.2 in ASCE 7-10).

Top floor acceleration

A time series of resultant acceleration at the top floor, $a_r(t)$ is

$$a_r(t) = \sqrt{[\ddot{x}_{top}(t) - D_{top,y}\ddot{\theta}_{top}(t)]^2 + [\ddot{y}_{top}(t) + D_{top,x}\ddot{\theta}_{top}(t)]^2} \quad (6)$$

where accelerations $\ddot{x}_{top}(t)$, $\ddot{y}_{top}(t)$, and $\ddot{\theta}_{top}(t)$ of the mass center at the top floor pertain to the x , y , and θ (i.e., rotational) axes, and $D_{top,x}$ and $D_{top,y}$ are the distances along the x and y axes from the mass center to the point of interest on the top floor.

The resultant value of Eq. (6) is used, rather than accelerations along the principal axes, because peak acceleration is of concern for human discomfort regardless of its direction. While ASCE 7-10 does not provide wind-related peak acceleration limits, for office buildings a limit of 25 mg with a 10-year MRI was suggested by Isyumov et al. (1992) and Kareem et al. (1999).

APPLICATION AND RESULTS

A 60-story reinforced concrete building with rigid-floor diaphragm in this study has dimensions 45.72 m in width, 30.48 m in depth, and 182.88 m in height and is known as the Commonwealth Advisory Aeronautical Research Council (CAARC) building. It has a moment-resistant frame structural system consisting of 2880 columns and 4920 beams, and is similar to the structural

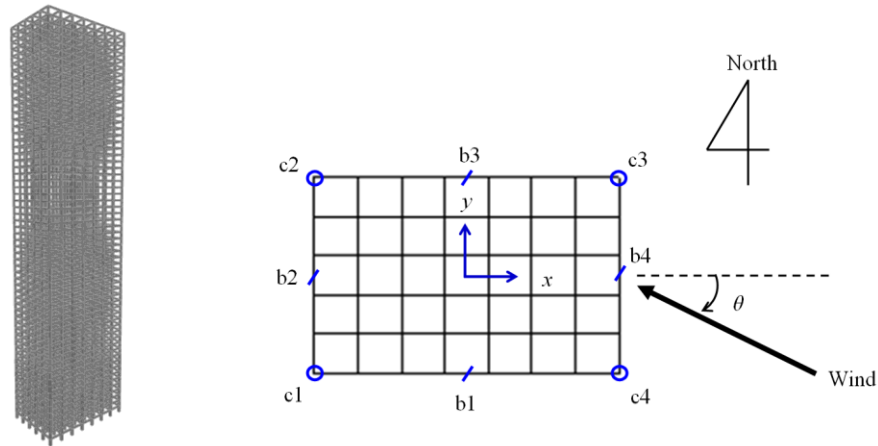


Figure 2. Schematic and plan views of a building

system studied by Teshigawara (2001). The building was assumed to be located near Miami, Florida and to have suburban exposure. The long side of the building was assumed to be normal to the South-North direction. The damping ratio was assumed to be 2 % in all three lowest modes. The building is categorized as Occupancy Category III, whose design MRI is 1700 years.

To illustrate the estimation of structural wind effects on the CAARC building we used synchronous pressure time histories at a total of 120 pressure taps obtained at the Prato (Italy) Inter-University Research Centre on Building Aerodynamics and Wind Engineering (CRIACIV-DIC) Boundary Layer Wind Tunnel. The model scale was 1:500, and the sampling frequency was 250 Hz. The reference model mean wind speed was 23.2 m/s at the top of the building.

For strength design, demand-to-capacity indexes (DCIs) corresponding to various mean recurrence intervals (MRI) were obtained for structural members of the building. Figure 2(a) shows the DCIs for the corner column c1 with respect to MRIs. Because ratios of peak overturning moments based on DAD and on ASCE 7 are less than 0.8 for MRI = 1700 years, and the corresponding DCIs are adjusted by multiplying the original indexes by adjustment coefficients γ of 1.19. For the corner columns, DCIs for axial force and bending moments interaction (B_{ij}^{PM}) were 0.95 to 1.00, while the DCIs for the shear force and torsional moment interaction (B_{ij}^{VT}) were 0.44 to 0.73. For the spandrel beams, B_{ij}^{PM} ranged from 0.44 to 0.74 and B_{ij}^{VT} were from 0.32 to 0.53.

For serviceability design, DAD provided inter-story drifts along column lines and top-floor accelerations. Figures 2(b and c) show inter-story drift ratios of a corner at the 44th floor and accelerations of a corner at the top floor with respect to MRIs. The largest inter-story drift (i.e., y-direction drift in this study) was $d_{i,y} = 0.0029$ for MRI = 20 years on the four corners at the 44th floor, which is larger than $1/400 = 0.0025$. The top-floor peak resultant accelerations were 27.9 mg (i.e., milli-gravitational acceleration) for MRI = 10 years, rather than 25 mg. The design is seen to be governed by serviceability constraints.

DAD's efficiency in determining building response corresponding to various set of simulated pressure time histories makes it possible to assess the significance of the various parameters that determine the response and of uncertainties in those parameters.

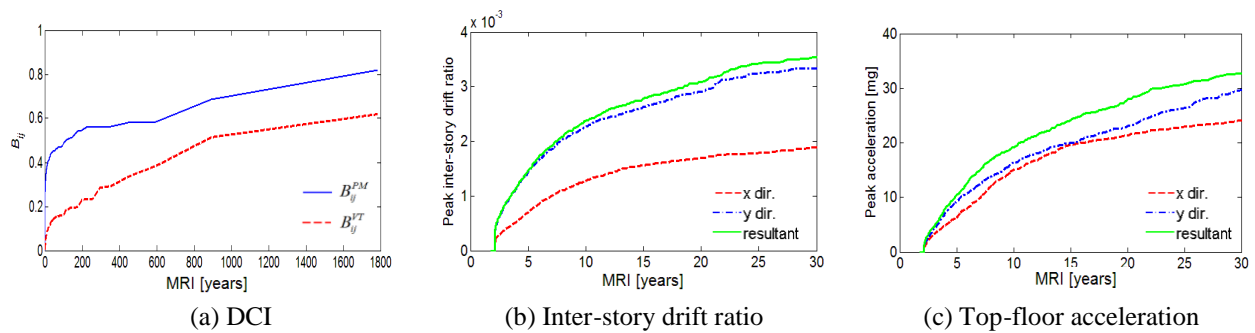


Figure 3. MRI-based peak wind effects

CONCLUSIONS

This paper presented the development of a Database-Assisted Design (DAD) procedure for reinforced concrete buildings, and its application to a 60-story building. The DAD procedure

performs dynamic analyses using simultaneous time-series of aerodynamic pressure data and establishes response databases of wind effects for a sufficiently wide range of wind speeds and for a sufficiently large number of wind directions. The databases depend on the building's aerodynamic, geometric, structural, and dynamical features, and are independent of the wind climate. DAD appropriately accounts for wind directionality using: wind climatological data that may need to be augmented by simulation (for the description of a procedure for developing augmented wind speed data sets see Yeo 2011); aerodynamic data; and micro-meteorological data. Estimated peak responses obtained from DAD are estimated for the requisite mean recurrence intervals. This requires that the estimates be performed in the wind effects space.

The procedure was illustrated through its application to a specific design of the CAARC building. The design approach presented in this paper provides more accurate and clearer predictions of wind effects than conventional approaches, and is expected to be more economical and efficient when used in conjunction with optimization. Software for implementing the DAD procedure used in this study is available on www.nist.gov/wind.

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